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**SIMULATION OF DYNAMICS AND CONTROL  
OF A TWO-PLY PAPER MACHINE**

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# Simulation of Dynamics and Control of a Two-ply Paper Machine

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## **ABSTRACT**

Past efforts to use model-based controls in the paper industry have not been successful due to the sensitivity of the model control algorithms to sensor or model error and to noise. To better understand the reasons for this sensitivity and to develop more robust techniques, we have developed a series of dynamic models at various levels of control complexity. A single stirred tank model is used to illustrate the disturbance rejection and set-point tracking of various control loops. A dynamic two-ply liner paper machine model is used to show the systems wide effects of individual control loops during upsets such as sheet breaks and the response to changes in basis weight. Feedforward and selective control strategies proved to be essential for stable control of fiber flow to the machine and, therefore, to controlling basis weight. Improved numerical techniques were also needed for stable solutions of the dynamic equations. The models have been integrated with a real-time database making it possible to run the system faster than real-time with current input from the DCS. In this mode the model could provide optimal control to portions of the papermachine to minimize the effects of errors in consistency and the stability problems associated with feedback. The results shown here merely illustrate the variety of control concepts which could be evaluated.

## **KEY WORDS**

Dynamics, process control, simulation, multi-ply paper machine, consistency control, basis weight control.

## INTRODUCTION

The most significant applications of control hardware and sensor technology in the paper industry have been in the paper machine area particularly in machine direction and cross machine basis weight, moisture, and caliper control (Lindeborg, 1988). These applications rival those in other industries for sophistication and complexity. However, aside from the use of feedforward algorithms in the control of dry fiber flow, very little advanced control theory has been successfully applied in the paper industry. Most loops continue to use conventional feedback control. Aside from the headbox, slice, and wire, paper machine wet-end controls are comprised primarily of flow, level, and consistency controls as well as refiner plate gap (Lavign, 1977). Consistency measurement is perhaps the most crucial and the most prone to error. Headbox consistency usually cannot be reliably measured and must be adjusted by feedback from the basis weight sensors at the dry end of the machine.

Advanced adaptive control schemes have been most successfully applied to reduce the variance of moisture and basis weight (Åström, 1964; Åström and Bohlin, 1966; Cegrell and Hedqvist, 1973; Åström and Haggman, 1974; Al-Shaikh, 1978). However, most attempts to employ predictive and model-reference control commercially were abandoned due to sensitivity to model or signal error and to noise. The apparent failure of predictive algorithms has given way to the use of artificial intelligence tools such as expert systems and neural networks. These alternatives to predictive control allow typical noise and signal patterns to be "learned" and once recognized to allow the appropriate control action to be taken. There is no conscious attempt to directly relate control action to specific signal components, however. Noise and signal error can result from errors in consistency sensors as well as vibrations and complex fluctuations in pumps, valves and pipe systems.

It is well accepted that steady-state models represent typical process conditions quite accurately. For many years dynamic models have been used successfully (Beecher, 1963; Parker, 1981; Sullivan and co-authors, 1965) to predict transient responses to process disturbances such as machine breaks (Bussiere et al, 1988) and grade changes (Miyanishi, 1988). It was somewhat easier to simulate dynamic behavior on a paper machine because most of the dynamics were caused by tank holdups, while many other systems such as steam and power, pulping or recovery contained many different types of dynamic elements. The failure of predictive models to represent the detailed variability may lie in the failure to simulate and correct for noise and random disturbances. The recent work in robust model reference control may yet prove successful in overcoming these problems (Landau, 1979). A sequential modular system with the appropriate noise, sensor error, and disturbance characteristics may be useful in interpreting actual machine data. It may be possible to reconcile the errors in consistency using the systems wide model to more accurately control flows and basis weight.

## OBJECTIVES

In this work our objectives are to develop improved and more robust control algorithms which could overcome some of the problems associated with "advanced control." Our short-term objectives are to develop dynamic models of single tank control and then to apply these to more complex multi-tank control schemes. Our long-term goal is to incorporate these models into existing control systems. Our control algorithms are based on simulation models which include the major dynamic elements of the paper machine. Although simpler systems could have been devised, the application which we will discuss is of a two-ply liner paper machine at a mill in the Southeastern United States.

This application was first developed as a steady-state model which included highly detailed calculations of the fourdriniers and multi-ply formers, the press sections, dryer section, and white water system. The original work was used to investigate the sensitivity of multi-ply compressive strength to process variables such as OCC content, refiner power, press load, fiber orientation, and MD restraint. The model used the performance attribute system developed at IPST to predict end-use performance and properties such as tensile, optical, and elastic characteristics of paper (Jones, 1989). However, in order to control or optimize end-use performance, it is first necessary to control more fundamental factors such as fiber flow, sheet basis weight, and caliper. The control schemes developed so far are limited to the control of dry fiber flow, consistency, and tank levels in the approach system of the paper machine. High frequency fluctuations due to manifold, headbox, and slice dynamics are beyond the scope of the current sequential modular system.

The behavior of the single tank control system to set-point changes and disturbances is discussed first. The single tank control scheme is then applied in a somewhat idealized and modified form to the multi-tank system of the two-ply machine. In each case the closed-loop response of the manipulated or control variables is shown after a load or set-point change.

## ELEMENTS OF THE DYNAMIC SYSTEM

The dynamics and control elements are a fairly new addition to the steady-state process simulator (MAPPS, 1993) described many times in the past. The concept of dynamic simulation with a sequential modular simulator requires the following assumptions and simplifications:

- (1) The mass and energy balances are strictly converged only at the steady state. However, for small time steps and small perturbations, errors associated with non-converged tear streams are negligible.
- (2) Dynamic elements are represented in two ways. Truly dynamic elements such as plug

flow vessels and stirred tanks are treated rigorously, while many other potentially dynamic unit operations such as evaporators, heat exchangers, flash units, etc., are currently treated with instantaneous, i.e., steady-state models followed by first-order lags or time delay elements to lag the signals from the unit.

- (3) Elements such as piping systems which are both rapid and simultaneous are not handled. Signals are communicated at the rate at which the flowsheet is updated or scanned. This scanning frequency is related to the rate at which the computations are made (i.e., the hardware and software) rather than to the simulation time step. If the computer is sufficiently fast relative to the smallest time constants in the system, the approximation will not affect the results.
- (4) The order in which the signals are updated and passed in the flowsheet depends on the calculation order which is the order in which the process modules are listed.
- (5) The wire and headbox dynamics are not considered. The time delay between the thick stock flow and the dry end basis weight, which was found to be approximately 70 seconds (Balchen, 1988), has no significant effect on the current dynamics but will be included in future versions.

### **Dynamic Controller**

The dynamic system is controlled by means of a controller block (DCONTRL) which is placed at the beginning and end of the calculation order. The first instance of the DCONTRL block initializes the time step, the current time, and the maximum time. A variety of modes can be specified. In one mode the dynamics are run continuously with no maximum time. The second instance of the DCONTRL block checks for the current simulation time, updates the time, and passes control back to the beginning of the sequence. This block is not an actual process operation but is needed to run the simulator much as the supervisor block used by Sullivan and Schoeffler (1965).

### **Stirred Tank and Plug Flow**

The dynamic tank is similar to those described previously. However, this tank also incorporates the performance attribute variables in MAPPS such as fiber length and width distributions, CSF, and many other fiber characteristics. These are mixed dynamically in a first order model similar to that of composition. The tank uses a pseudoanalytical integration method which is much more stable and accurate than the Euler methods and faster than predictor-corrector or multistep techniques. The essential feature of the method is that the first-order differential equation is treated as exact over each time step and is therefore integrated analytically assuming the coefficients are constant. Given the general form,



$$\frac{dY}{dt} = A + BY \quad (1)$$

rather than using the explicit finite difference approximation,

$$Y^n = Y^o + (A + B^o)\Delta t \quad (2)$$

or the implicit finite difference approximation,

$$Y^n = \frac{Y^o + A\Delta t}{1 - B\Delta t} \quad (3)$$

the "exact" solution is used instead,

$$Y^n = -\frac{A}{B} + \left(\frac{A}{B} + Y^o\right)e^{B\Delta t} \quad (4)$$

This same method is applied to all transient balances. In the case of coupled balances, the coupled linear system can be solved directly at each time step in terms of the eigenvalues of the matrix of coefficients.

The plug flow unit is used to simulate a true plug flow operation such as a batch, continuous digester, or a bleach tower, or simply to delay a signal by a specified dead time. Dead time is neglected in these applications.

Four types of disturbances, random, sinusoidal, step, and ramp, are modeled with four blocks which can be programmed to vary the disturbance parameters in a variety of ways. For example, a random block can be used to randomly vary the frequency or phase lag of a sinusoidal block. The step and ramp can be programmed to occur at a series of specific simulation times. SINE and STEP are illustrated in examples. The step is designed to change 1 to N variables at independently specified times. The other modules are set up to change N variables in a specific way over a specified period of time.

## Control Algorithms

The feedback controller (CONTRL) is based on a finite difference form of the standard

PID algorithm. A feedforward control block (CCONSIS) based on a steady-state mass balance (Stephanopoulos, 1984) performs feedforward control of consistency. This module "senses" the composition and flows of the **feed** streams to the stirred tank and adjusts a dilution flow of a given consistency to maintain a set-point consistency. A secondary level control override feature may also be switched on. If the level drops below or rises above specified upper and lower limits, the dilution flow is adjusted to stay within the bound, and the consistency control is temporarily suspended. Given an exact value of the consistency, this module provides ideal disturbance rejection but is not sufficient for set-point changes. Future versions will include a dynamic feedforward algorithm which "inverts" the dynamic mass balance thus allowing for set-point tracking.

### **Control Logic**

A logic block, called LOGIC, allows the specification of a logical IF - THEN condition which is tested as part of a control scheme. If the condition is true, the output of the module is one value, while if the condition is false, the output is a second value. In the future this feature can be generalized to allow the user to develop complex logical networks without having to perform any programming.

### **Variable Computations**

Variables may be manipulated and new variables generated for use with the control schemes through use of the MATH block. This block performs elementary operations such as ratios, sums and differences, or multiplication by a constant thus allowing variables to be transformed for use by control modules. By combining LOGIC, MATH, and CONTROL blocks, it is possible to construct realistic dynamics and control strategies.

## **APPLICATIONS**

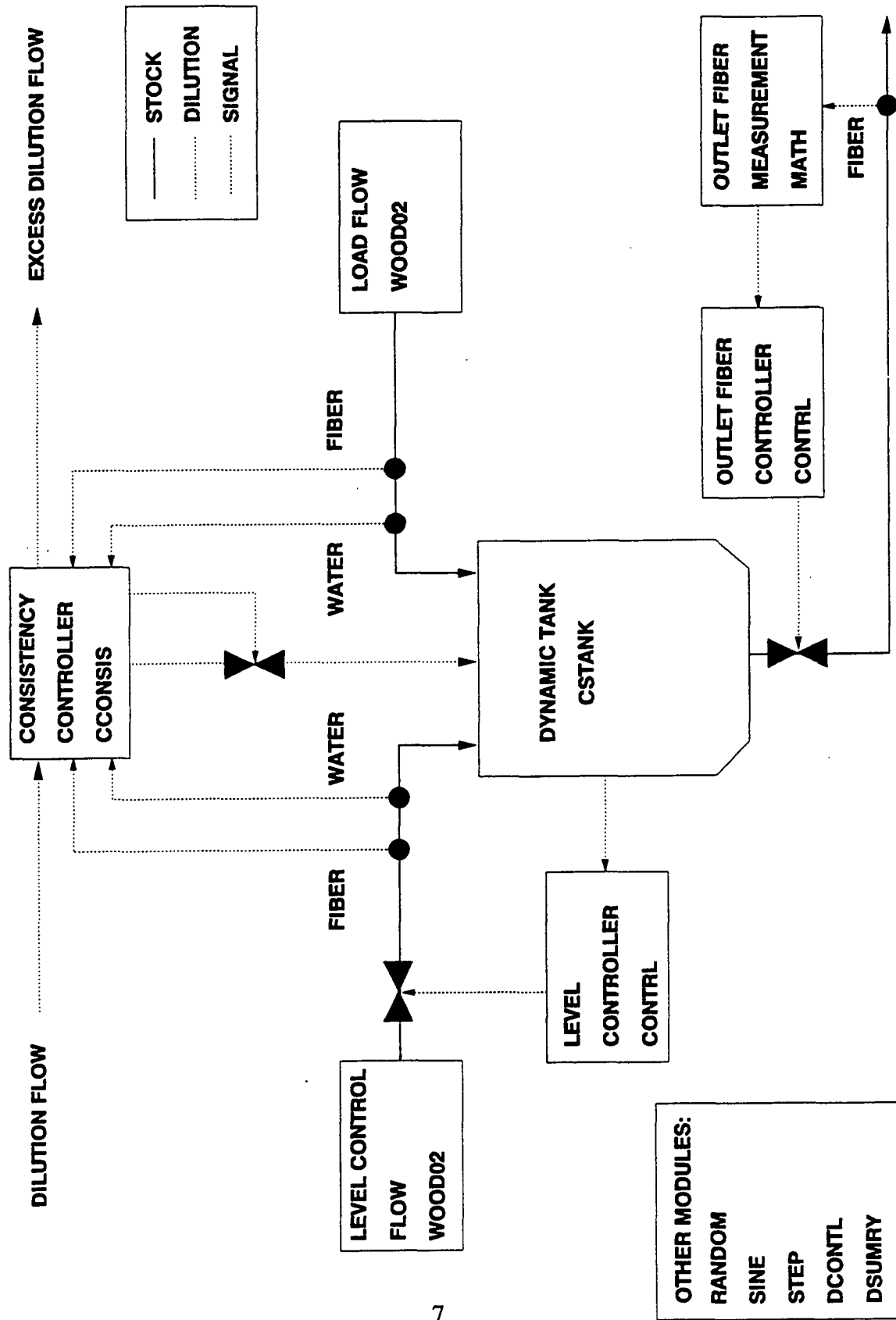
Basis weight control requires good control around each major tank in the approach system. The control of consistency, fiber flow and level are described first followed by an example of dynamics and control following a sheet break at the wet end of the top ply fourdrinier.

### **Single Stirred Tank - Consistency, Level, and Fiber Flow Control**

Dynamic simulation and control of a single stirred tank is shown in Figure 1. The tank shown in the center mixes three streams together: two stock streams generated by WOOD02 blocks and a dilution stream. By sensing the incoming consistencies and flows in the entering streams, feedforward consistency controller, CCONSIS, manipulates the dilution flow to control outlet consistency. Dry fiber flow is controlled through a feedback loop using a PID controller (CONTRL) to sense the outlet fiber flow computed by the MATH block and by manipulating the outlet flow from the tank. Level is controlled by adjusting one of the two fiber stock streams from one WOOD02 block by a feedback

FIGURE 1

# DYNAMIC TANK



loop. Both feedback controllers use PI control where both proportional gain and reset time constant are set manually for rapid rise time and minimum overshoot. Set-points are defined on tank level, discharge consistency, and BD fiber flow rate. The loops are capable of both disturbance rejection and set-point tracking with no permanent offset.

Disturbances are introduced in the form of oscillation in the consistencies of both the level control flow (average of 4%) and the load flow (average of 4.5%) from blocks WOOD02. The SINE block causes the fiber flow rate in the fiber source blocks (WOOD02) to oscillate according to a specified frequency and amplitude. A RANDOM block causes the frequency of the disturbances to vary randomly. As shown in Figure 2, the disturbance (load) fiber flow oscillates between 198 and 202,000 lb/hr with a randomly varying frequency. Load and level control flow stream consistencies shown in Figure 3 oscillate between 4 and 5% and 3.5 to 4.5%, respectively, with randomly varying frequency. The time-smoothed period is 0.5 to 0.7 hours.

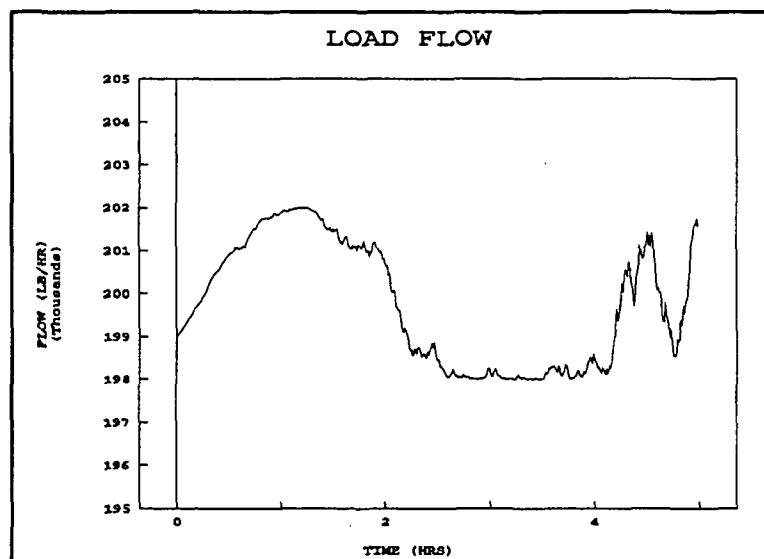


Figure 2. Load Fiber Flow vs. Time

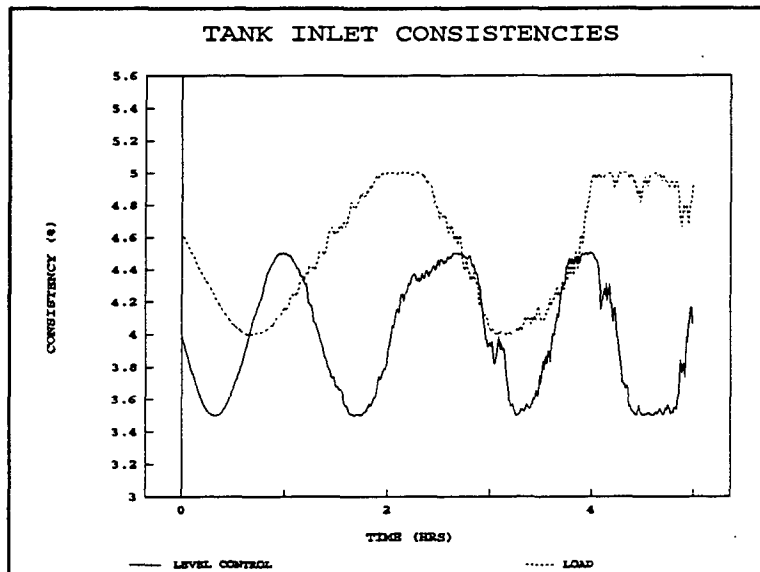


Figure 3. Load and Level Control Consistency vs. Time

Under normal operation and before the set-point change at 2 hours, the fiber-flow feedback controller maintained the fiber flow at the setpoint of 10,000 lb/hr as shown in Figure 9. Tank volume remained near 3,000 cu. ft. as shown in Figure 4. Tank and discharge stream consistencies were held constant by the feedforward controller with ideal sensor inputs as shown in Figure 6. Dilution flow varies as shown in Figure 5 in response to oscillations in tank inlet flows and consistencies.

### Response to Set-Point Change

At 2 hours the fiber flow set-point was increased from 10 to 12,000 lb/hr as shown in Figure 9. Tank volume dropped and then returned to the previous level as shown in Figure 4. Level control flow increased rapidly and then settled down to a new average level of 50 to 60,000 lb/hr as shown in Figure 8. Dilution flow increased initially and then resumed a similar oscillation as shown in Figure 5.

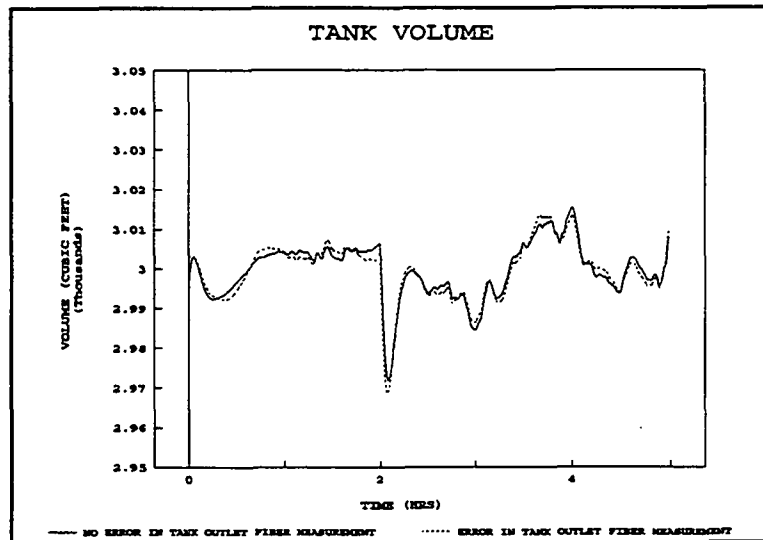


Figure 4. Tank Level vs. Time

As intended, the feedforward control adjusted dilution flow rapidly to the varying fiber flows into the tank. Tank and outlet stream consistencies remained at 3% (Fig. 6). This case is based on the assumption of accurate consistency measurements into and out of the tank which is rarely the case in actual practice. The effects of an error in the tank outlet consistency or fiber flow shown in Figure 7 caused the tank volume response to overshoot slightly and to lag behind the case where consistency is accurately measured (Fig. 4). The level control flow is lagged by the error in the outlet consistency but the effect is not significant (Fig. 8). The dilution flow is barely affected by the error in the outlet consistency measurement because it is manipulated by the feedforward controller which receives accurate inlet consistency values. Similarly, the outlet consistency is held constant (Fig. 6). The outlet fiber flow oscillated around the true value, but the response to the set point change was not affected by the error as shown in Figure 9. The difference between the actual and the measured outlet fiber flow (based on the consistency) shown in Figure 7 indicated that the controller response to the step change was not adversely affected but that significant oscillations resulted. If similar random errors were applied to the inlet flow consistencies, the feedforward controller would not have responded with the same accuracy, and the overall control would have been adversely affected.

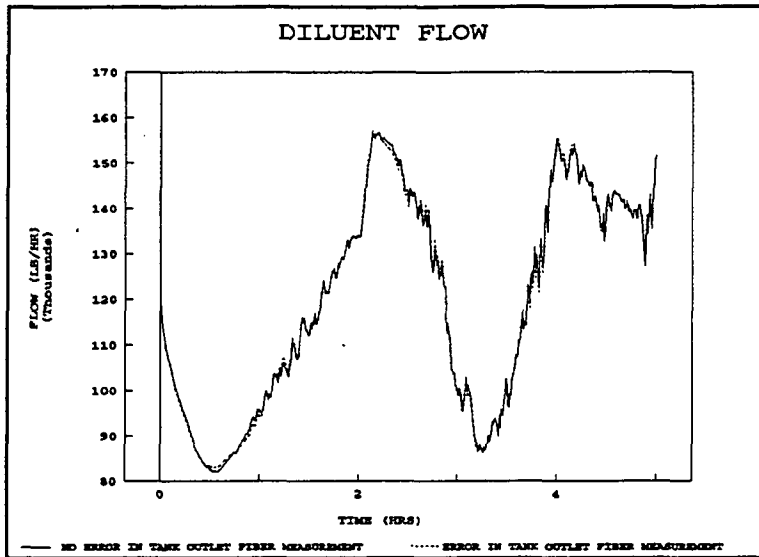


Figure 5. Dilution Flow vs. Time

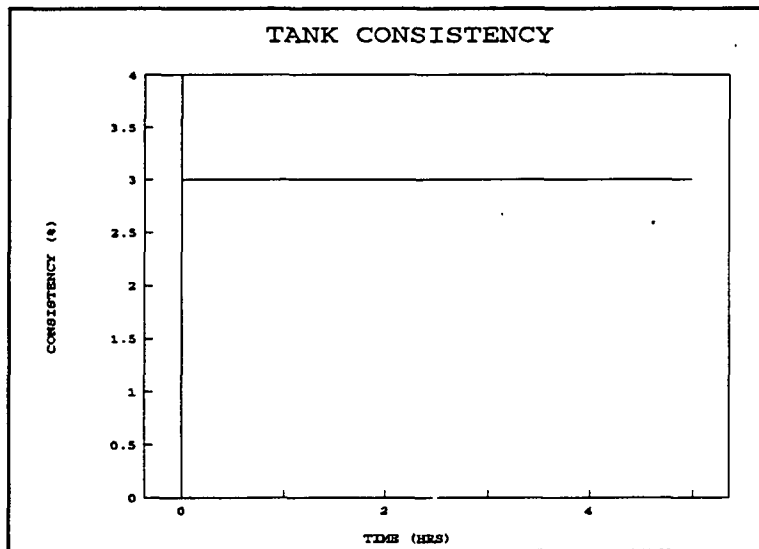


Figure 6. Tank Consistency vs. Time

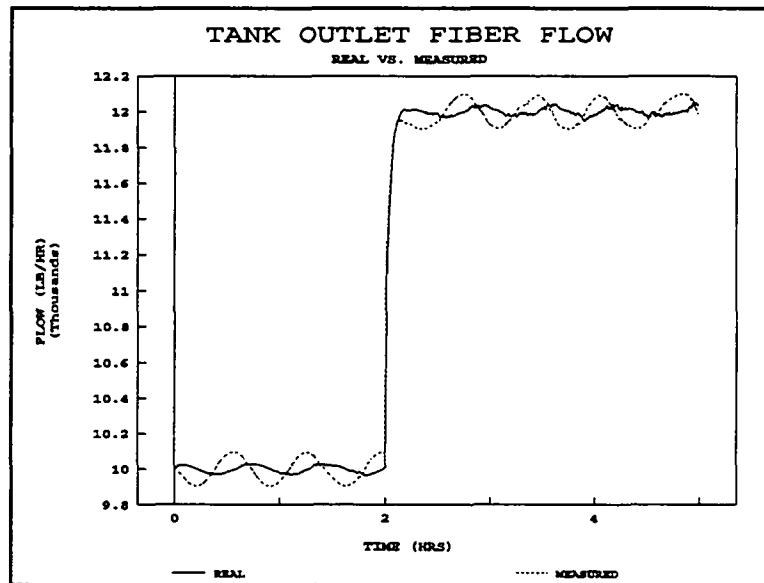


Figure 7. Measured and Actual Outlet Fiber Flow vs. Time

The feedforward controller would in reality not be able to manipulate dilution flow as rapidly as shown due to the limitations of the control valves and capacity of the header system. Therefore, this feedforward system should have passed a signal to a control valve which is governed by a first- or higher-order response. Also, the header itself could have been modeled as a first-order lag plus deadtime system to mimic the actual header response.

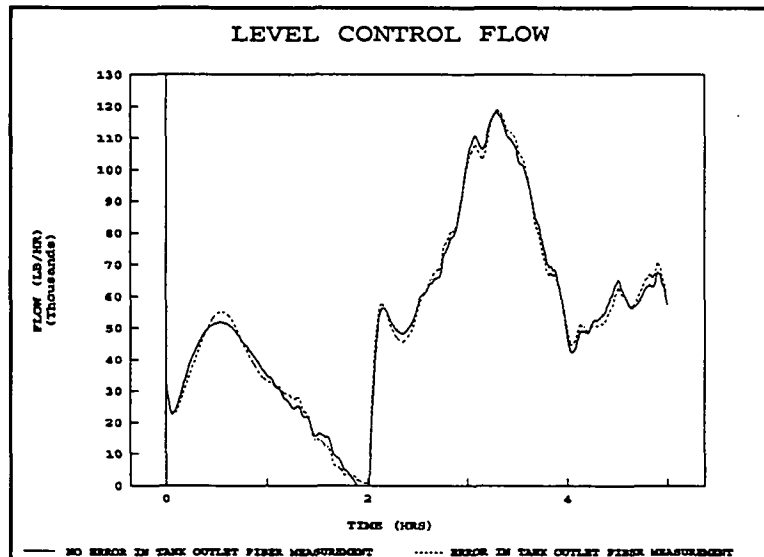


Figure 8. Level Control Flow vs. Time



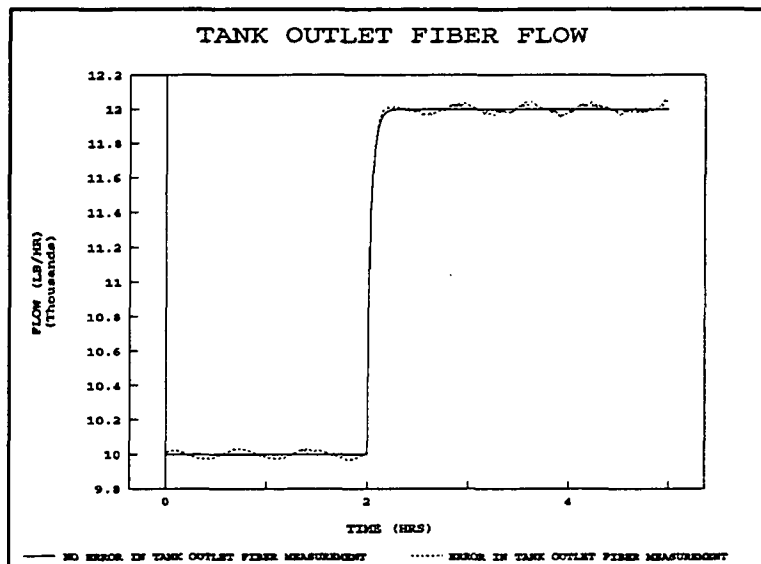


Figure 9. Tank Outlet Fiber Flow vs. Time

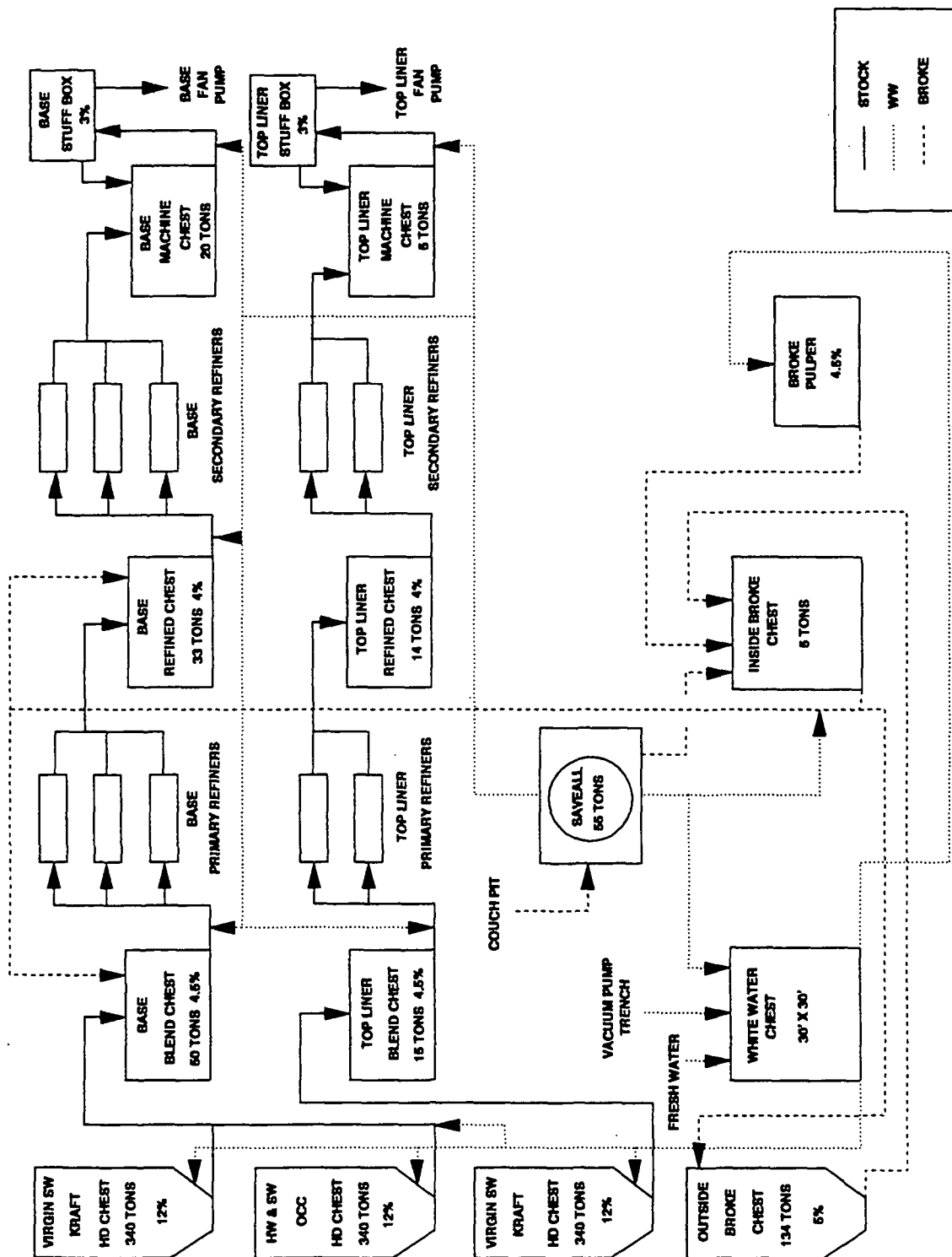
### Multi-ply Liner Dynamic and Control

Applications were also developed to simulate dynamics and control on a two-ply liner paper machine model shown schematically in Figures 10 and 11. The unique feature of these models is the detailed retention and performance attribute models in the wire section and press sections. The attributes of each ply in the two-ply structure, generated in the multi-ply forming block, are altered as the stream passes through the press and dryer sections resulting in a multi-ply structure with unique properties at the dry end of the machine. Control loops are similar to those shown previously except that the feedback level control is maintained between upper and lower limits using an override feature of the feedforward controller. When level specifications are violated, the controller uses dilution flow to control level and temporarily suspends control of consistency.

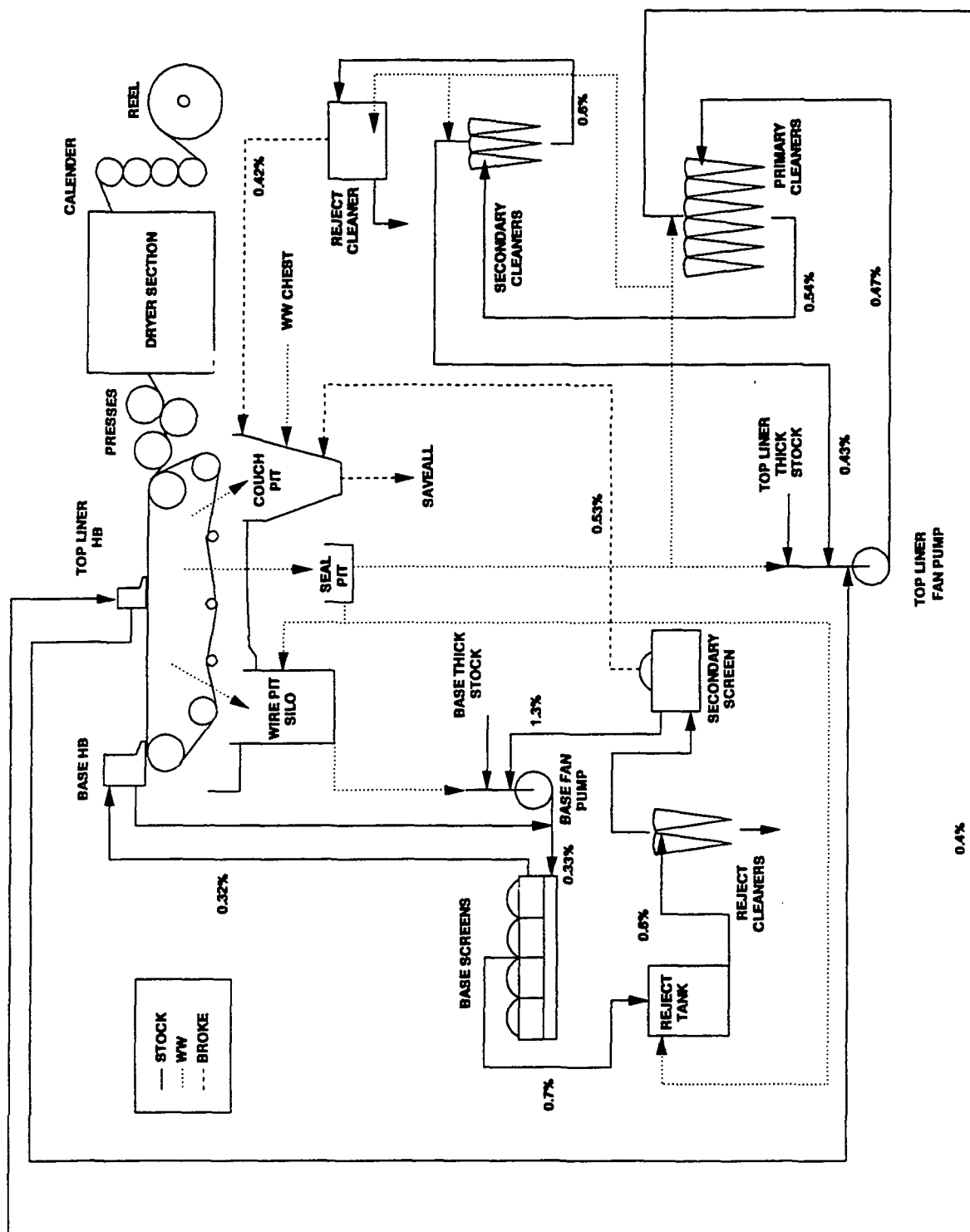
In this application the high density flows and consistencies were constant with time. Basis weight was maintained by controlling total dry fiber flow along each fiber line to each headbox. The most stable control was obtained when total fiber flow is controlled at the discharge of each of the major tanks in the approach system on both fiber lines. By controlling dry fiber flow, it was possible to not only control final basis weight but also to adjust more rapidly and with greater stability to changes in dilution flow and consistency along the fiber line.

FIGURE 10

# DYNAMIC TWO-PLY PAPER MACHINE



# DYNAMIC TWO-PLY PAPERMACHINE



## Machine Break

A sheet break between the end of the multi-ply former and the press was initiated at 0.3 hours, and the sheet was restrung at 0.7 hours. The break was simulated by a STEP block preset to change a split fraction in a SPLITTER block from 1 to 0 at the specified time. The resting operation was timed through the same STEP by resetting the SPLITTER from 0 to 1 at 0.7 hours. When the split occurred, the fiber flow dropped to zero at the wet end of the paper machine. As a result of the break and the small couch pit volume, the couch pit consistency, which is normally 0.025%, immediately increased to 0.11% and remained constant until the wire was restrung at which point the consistency dropped to the previous level as shown in Figure 12.

After the break, the flow increased from the couch to saveall system which led to increased flow to the broke chest. The broke chest volume was in a normal upswing which increases in response to the machine break as shown in Figure 13. The broke chest consistency also increases and then begins to decrease after the paper is restrung (Fig. 14). The feedback controller decreases the broke flow rate to maintain the proportion of broke in the base sheet when the machine is later restrung as shown in Figure 15. The base sheet refiner chest level and other approach tank volumes increase in a first-order fashion as shown in Figure 16. Figure 17 shows the expected variation in the basis weight signal at the dry end.

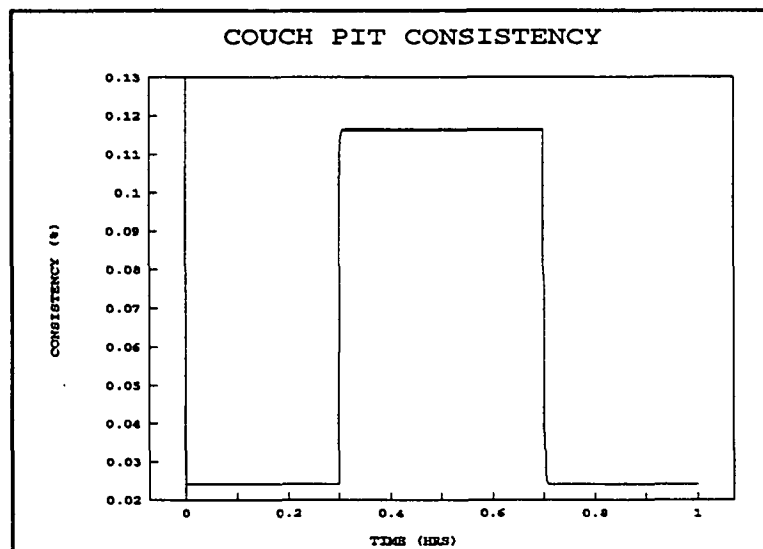


Figure 12. Couch Pit Consistency vs. Time

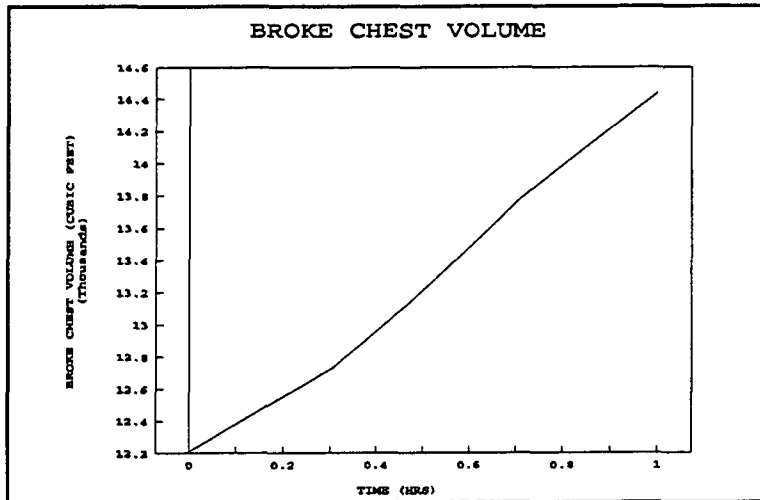


Figure 13. Broke Chest Volume vs. Time

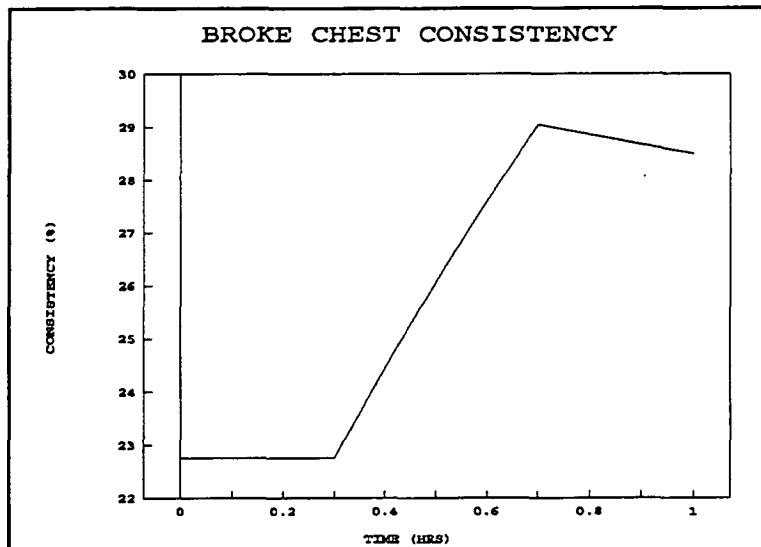


Figure 14. Broke Chest Consistency vs. Time

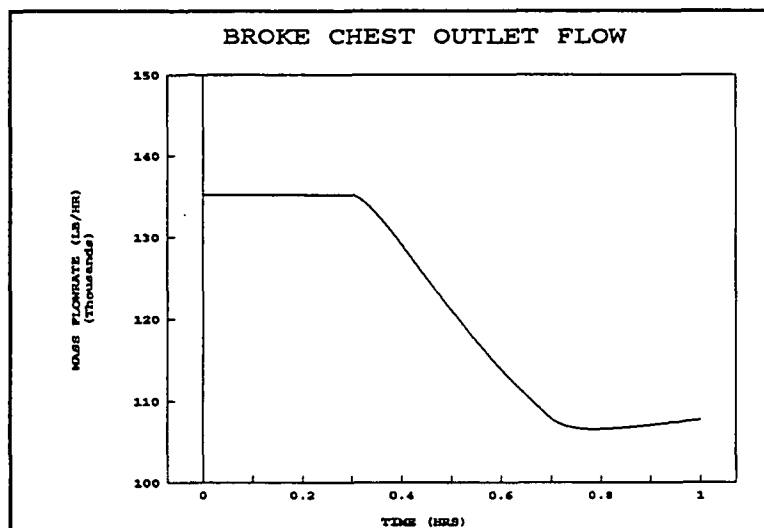


Figure 15. Broke Chest Outlet Flow vs. Time

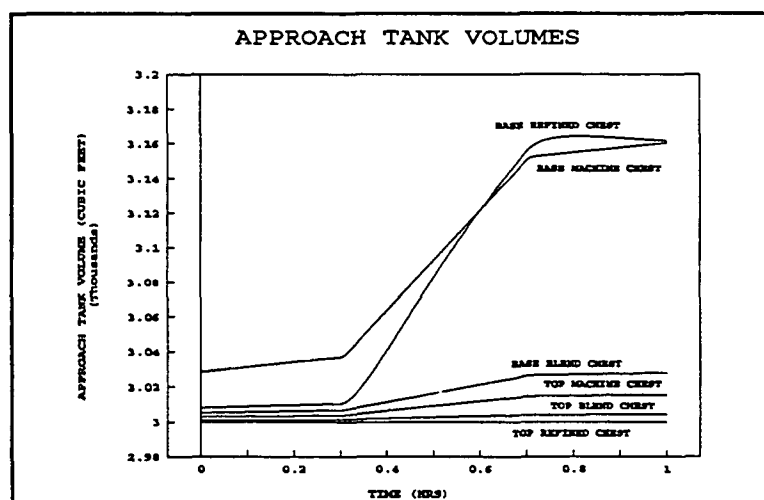


Figure 18

Figure 16. Approach Tank Volumes vs. Time

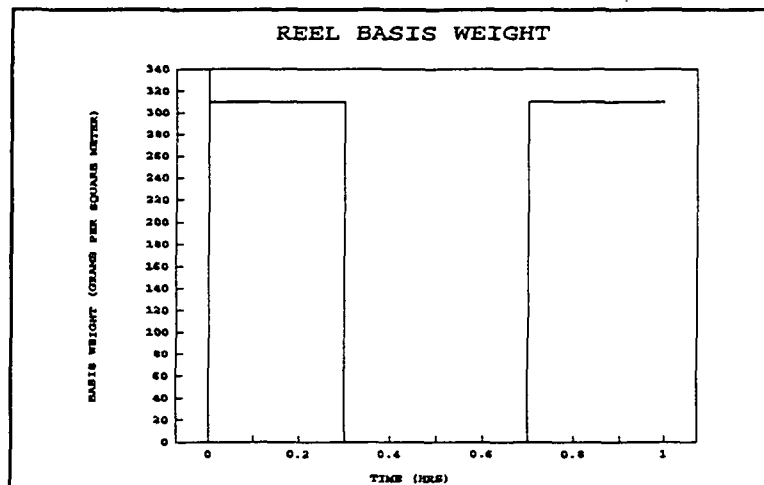


Figure 17. Reel Basis Weight vs. Time

## CONCLUSIONS

These applications illustrate the use of dynamic simulations to develop more robust control schemes for the wet end of the paper machine. On-line use of a systems wide simulation model of the wet end could provide a more reliable basis for robust adaptive and supervisory control which could overcome the deficiencies of previous efforts. Feedforward control of dry fiber flow is superior to feedback control for stable MD basis weight control provided the errors in the consistencies can be minimized. Sensitivity to consistency errors will be studied further.

Many other scenarios can be investigated with this system. For example, the effects on drainage, retention, and controller dynamics of variable CS freeness at the HD chests could be simulated. The effects of error in the upstream consistency meters on the feedforward control performance could be evaluated. Additional details such as control valves and machine delay should also be added. The step block could be used with other applications to simulate a set of discrete events.

## REFERENCES

- Al-Shaikh, A. M., "Advances in Paper Machine Control," ATCO-XVIII, Albuquerque, New Mexico (1978).
- Balchen, J. G., Mumme, K. I., **Process Control - Structures and Applications**, Van Nostrand Reinhold, NY, p. 407 (1988).
- Beecher, A. E., "Dynamic Modelling Techniques in the Paper Industry," **Tappi** 46(2) (1963).

- Bussiere, S, Roche, A., Paris, J., "Analysis and Control of the White Water Recirculation in an Integrated Newsprint Mill: A Dynamic Simulation Approach," Proceedings CPPA Process Simulation Symposium, Quebec, CAN, p. 91 (1988).
- Cegrell, T., Hedqvist, T., "Successful Adaptive Control of Paper Machines," 3rd IFAC Symp. on Ident. and Sys. Par. Est., The Hague, (1973).
- Jones, G. L., "Simulating End-Use Performance," **Tappi** 72(10):189 (1989).
- Landau, I. D., **Adaptive Control - The Model Reference Approach**, Marcel Dekker, Inc., NY (1979).
- Lavign, J. R., **An Introduction to Paper Industry Instrumentation**, Miller Freeman, SF (1977).
- Lindeborg, C., "Simulation of the Cross-Direction Moisture Control," Proceedings CPPA Process Simulation Symposium, Quebec, Canada, p. 95 (1988).
- MAPPs Reference Documentation, Institute of Paper Science and Technology, (1993)
- Miyanishi, T., K. Iida, T. Iwatsu, "Dynamic Simulation for Efficient Paper Machine Grade Change," **Tappi**, p. 49-56 January 1988.
- Parker, P. E., DYSCO: A Modular, Dynamic Simulator for the Pulp and Paper Industry, **Tappi** 64(3):97-101 (1981).
- Stephanopoulos, G., **Chemical Process Control**, Prentice-Hall, (1984).
- Sullivan, P. R., Schoeffler, J. D., "Simulation of Stock Preparation and Fourdrinier Dynamics," **Tappi** 48(10): 552 (1965).
- Virtanen, P., "Computer Simulator for Paper Machine Wet End," Proceedings CPPA Process Simulation Symposium, Quebec, CAN, p. 85 (1988).
- Åström, K. J., "Control Problems in Papermaking," IBM Scientific Computing Symp. Control Theory and Applications, New York (1964).
- Åström, K. J., Bohlin, T., "Numerical Identification of Linear Dynamic Systems from Normal Operating Records," Proc. 2nd IFAC Symp. on Theory of Self-tuning Regulators, P. H. Hammond (ed.) Plenum Press, NY (1966).
- Åström, K. J., Borisson, U., Ljung, L., and Wittenmark, B., "Theory and Applications of Self-tuning Regulators," **Automatica**, 13, 457-476 (1977).



Åström, K. J., Haggman, B., "Paper Machine Dynamics," 4th IFAC/IFIP Int. Conf. on Dig. Comp. Appln. to Proc. Control, Zurich, p. 463 (1974).

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